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Interaction of solar power satellite with the space and atmosphere environment

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Abstract

In this paper, we present the concept of transmitting power without using wires i.e., transmitting power as microwaves from one place to another is in order to reduce the transmission and distribution losses. This concept is known as Microwave Power transmission (MPT) using SOLAR POWER SATELLITE (SPS). This paper describes the SPS interaction with space and the atmosphere environment and influence of the SPS and MPT on human health and bio-effects; it also summarizes the advantages of the SPS. We also discussed the technological developments in solar power satellite.

Keywords: Solar power satellite, MPT, Environment.

INTRODUCTION

Even though energy prices are relatively low today, the problem of where energy will come from in near future, how much it will cost, and how it will impact the world's environment has not gone away. It has two major facets. One is economics and the other is the environment. Energy is deeply enmeshed in both. A look at history and what is happening in the world today illustrates the problem. Two energy eras have elapsed during humanity's sojourn on Earth: the era of wood and the era of coal. The third is era of coil waning. Each new major source brings new economies and prosperity to the world. At the same time, world population is exploding and the underdeveloped nations yearn for the standard of living of the developed nations. Unfortunately that is impossible without sufficient cheap energy. The standard we have reached today has already imposed a severe penalty on the world's environment. Figure 1 shows three eras of energy world experienced. The question is: Can we develop a new energy source for the fourth era?

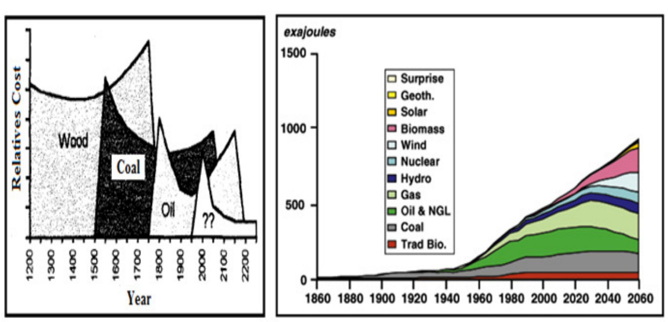

Fig 1. Three eras of energy & projected yearly growth of world's Energy consumption

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SOLAR POWER SATELLITES: BASIC CONCEPT

Basic idea of SPS is to collect the solar energy in orbit and send it to ground by microwave, laser beam or some other way .The concept of the Solar Power Satellite energy system is to place giant satellites, covered with vast arrays of solar cells, in geosynchronous orbit 22,300 miles above the Earth's equator. Each satellite will be illuminated by sunlight 24 hours a day for most of the year. Because of the 23" tilt of the Earth's axis, the satellites pass either above or below the Earth's shadow. It is only during the equinox period in the spring and fall that they will pass through the shadow. They will be shadowed for less than 1% of the time during the year. The solar cells will convert sunlight to electricity, which will then be changed to radio-frequency energy by a transmitting antenna on the satellite and beamed to a receiver site on Earth. It will be reconverted to electricity by the receiving antenna, and the power would then be routed into our normal electric distribution network for use here on the Earth. Figure 2 illustrates the concept.

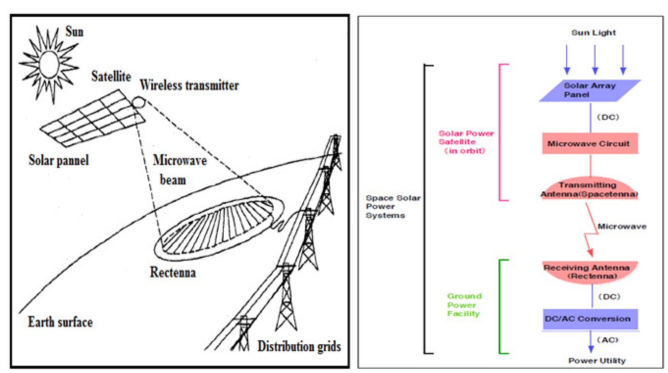

Fig 2. Components of Solar Power Satellites & Basic Conversion Process

The great advantage of placing the solar cells in space instead of on the ground is that the energy is available 24 hours a day, and the total solar energy available to the satellite is between four and five times more than is available anywhere on Earth and 15 times more than the average location. Testing has demonstrated that wireless energy transmission to the Earth can be accomplished at very high efficiencies. Tests have also shown that the energy density in the radio-frequency beam can be limited to safe levels for all life forms. The concept is simple; the technology exists.

INFLUENCE AND EFFECTS OF SPS

Atmospheric effects

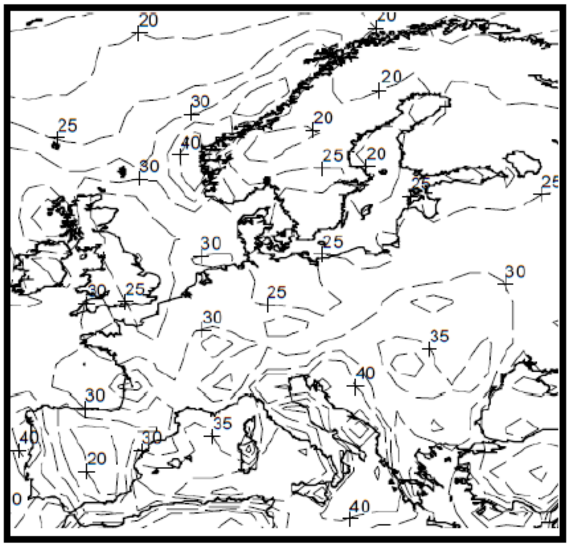

Fig 3. Rain rate (mm/h) exceeded for 0.01% of the average year (Rec. ITU-R P.837-4).1

Rain rate (mm/h) exceeded for 0.01% of the average year (Rec. ITU-R P.837-4) [1].Very few groups have worked on possible effects of microwaves on the atmosphere. Studies presently available refer to potential effects via heating of the ionospheric electrons or via ionization of the air. Observations of transient luminous events (sprites, blue jets, elves) in the upper atmosphere set basic questions on the electrical processes that develop in the Earth environment. It is clear that new studies are needed on all phenomena that may influence the atmospheric electrical conductivity and thus the global electric circuit. Heating of the ionospheric electron population may affect the ionospheric plasma and the atmosphere in different ways. The effects are probably more important between 100 and 250 km where the main chemical process controlling the ionospheric plasma concentration is the electronic recombination of O2 + and NO+. They obviously depend on the level of enhancement in the electron temperature. The rain attenuation can be calculated based on ITU-R PN618[2]. In case of Tokyo, the specific attenuation γR = 0.2dB at 5.8GHz since its rain rate is 50mm/h for 0.01% of the time (about 52.5 minutes per year). Rain rates for a part of Europe are shown in Fig. 3. Since the effective path length Le = 4.5km, the value of attenuation A=0.9dB (81%). However, γR = 0.1dB and A= 0.45 dB (90%) at 5 GHz. These values are smaller in Europe due to less rain as shown in the figure. The microwave SPS beam is scattered by rain or hail[3]. For a rain rate, *R* = 50 (mm/hour), frequency of 2.45 GHz, and the elevation angle of 47 degrees, the attenuation is about 0.015 dB/km. Furthermore, the maximum interference intensity *P* (W) received by an antenna for terrestrial radio relay links near the rectenna site for a power density of 23 mW/cm2 is *P* = 6.7×10-11*R*1.4*h,* where *h* (m) is the scatterer length. If *R* = 50~150 mm/hour and *h* = 3~10 km, then *P* = 0.1~1 mW. This level, however, would not cause nonlinear problems and interference can be removed by filters. Baranov et al[4] studied the effects of powerful microwaves on the atmosphere have been studied both theoretically and experimentally. Of particular interest are the experimental studies devoted to cleaning the troposphere of ozone. The idea involves artificially ionizing the air using high power electromagnetic waves. The necessary threshold field strength and intensity are 680 kV/m and 6 x 104 W/cm at 15 km, corresponding to a 6 GHz continuous wave. Since microwave pulses are used for the excitation of discharges, this breakdown electric field level can be several times higher. Although both levels are much higher than the values that will be achieved from the SPS, one sees that microwave radiation may have positive effects on the Earth environment. We also need to study and monitor potential negative consequences.

Ionospheric effects

Although much more published works are available, there are no conclusive observations or propagation models to provide a definitive view about the effects of microwave radiations on the ionosphere.

Ohmic heating

The first obvious effect of high power microwaves on the ionosphere is resistive or Ohmic heating. The absorption of the radio waves can be calculated from the electron density and electron-neutral collision frequency profile. The effect is largest in the lower ionosphere (D and E regions) where the collision frequency is highest. Although the effect is expected to be small with increasing frequency, it could still be significant. Several authors[5] have calculated the heating effect of 3 GHz waves. They estimate that, for a power density of about 16 mW/cm^2. The electron temperature could increase from about 200 K in the E region to about 1000 K. A temperature increase would result in a decrease of electron density because of a decrease in the temperature-dependent recombination rate of O2 + and NO2+. In the D region an increase in the attachment rate to O2 + also reduces electron density. To our knowledge no measurements of electron heating from high power microwaves in the ionosphere exist. The reason is probably two-fold: the difficulty of measuring electron temperatures on short time scales in the D region, and the lack of microwave heating experiments. Even if VHF and UHF radars of sufficient power-aperture produce heating effects, it is difficult to use them as both heating and measuring devices. It should also be noted that the heating effects may not be well represented by Maxwellian electron distribution function analysis[6] that is often assumed in analysis of incoherent scatter radar data, so that standard analysis techniques may not be applicable.Microwave injections from a rocket have been tried[7] ,but ohmic heating effects could not be observed. The lack of measured microwave heating in the ionosphere should not cast doubt on the reality of Ohmic heating caused by powerful microwaves, but only points out the shortcomings of the attempts made so far to measure it. On this rocket flight, the expected heating effect was less than 100K, which was below the detection limit of the Langmuir probe. However, the illuminated plasma volume was very small.Because the ionospheric heating efficiency varies as the inverse square of the radio frequency, heating effects equivalent to those from high-power microwaves can be achieved at much lower powers by heating at a lower frequency. This is done using ionospheric modification or heating facilities that are simply high-power (~1MW) short-wave (2 to 10 MHz) transmitters radiating upwards using high gain (16 to 30 dB) antenna arrays. D-region Ohmic heating effects are clearly observable indirectly through the conductivity and current modulation experiments [9] and the sometimes dramatic heating effects on polar mesospheric summer radar echoes[10][11] Direct measurements of the temperature enhancement using incoherent scatter radar are, however, difficult and rare.[12]

Self-focusing effects

Thermal self-focusing takes place as a result of a positive feedback loop. Small natural density fluctuations give rise to a spatial variation in the refractive index, resulting in slight focusing and defocusing of the microwave. This slight differential heating of the ionospheric plasma results in a temperature gradient driving the plasma from the focused region and thereby amplifying the initial perturbation. Such effects are well known and have been studied from HF-heating experiments, but it is unclear how important this is for an under dense plasma where the microwave frequency is much greater than the plasma frequency.

Three-wave interactions

The heating effects discussed above are the result of non-resonant interactions with the plasma. Another effect of high power microwaves is the production of plasma waves through resonant interactions, in particular through parametric instabilities. There have been several theoretical predictions that microwaves at high power may produce instabilities in the ionosphere. Matsumoto and Matsumoto et al. demonstrated that the microwaves may decay into forward-traveling electron plasma waves (Raman scattering) or ion acoustic waves (Brillouin scattering) and a backward-traveling secondary microwave. The electron plasma waves could be Langmuir waves when the excitation is parallel to the geomagnetic field, or electron cyclotron waves for excitation perpendicular to the field. Dysthe et al.[14] and Cerisier et al.[15] examined the case of two powerful microwaves having a frequency difference equal to the local ionospheric plasma frequency, typically 2 to 10 MHz. The ponderomotive force, which is proportional to the product of the two electric fields, can be strong enough to excite a parametric instability that results in Langmuir waves being produced. One result of a ground-based radar experiment near 1 GHz16 shows that such effects may indeed take place in the ionosphere. The three-wave interactions are expected to be most effective in the F region, above about km. Apart from the radar experiment of Lavergnat et al.,[16] there is, to our knowledge, only one other report of plasma waves being caused in the ionosphere by powerful microwave transmissions. This was from a 830W, 2.45 GHz transmitter on a mother-daughter Japanese rocket experiment (MINIX) where electrostatic electron-cyclotron waves at 3/2 the local electron gyrofrequency and electron plasma waves above the local plasma frequency were observed[17][7] and presented in a poster review.It was found that the excited waves differed from the initial theoretical expectations[18] in that the line spectrum expected from a simple three-wave coupling theory was in fact a broad spectrum, and the electron cyclotron harmonics were stronger than the Langmuir waves. Both these features could be successfully modeled using a more realistic computer simulation[19] where the nonlinear feedback processes were fully incorporated.From these simulation results, it was estimated that 0.01 percent of the microwave beam energy from the SPS would be converted to electrostatic waves. In conclusion, there have not been enough experiments with powerful microwaves in the ionosphere to determine with confidence the importance of instabilities as a loss mechanism for the beam and as a source of plasma waves and heating of the ionosphere. In the neighborhood of the satellite the power density will be high and its effects on the ionosphere will be examined experimentally. Care must be taken in the choice of frequency separations if multiple frequencies are used to beam down the power. Effects on the atmosphere are not expected.

Effects of electric propulsion on the magnetosphere

In the process of SPS construction, large high-power electric propulsion systems are needed. The electric propulsion systems inject heavy ions accelerated by electrodes powered by the photovoltaic cells. For transformation of orbits around the equator,the heavy ions are injected perpendicular to the Earth's magnetic field. The injection can strongly disturb the electromagnetic environment surrounding the ion engine in the plasma sphere and the magnetosphere through interaction between the heavy-ion beam and the magnetosheric plasmas. The interaction between the heavy-ion beam and the magnetic field has been studied theoretically[20][21] . Based on an MHD analysis, Chiu [20] predicted that Argon ion injection could excite Alfven waves propagating along the magnetic field down to the ionosphere and being reflected back. He also predicted that injected Argon ions can accumulate in the magnetosphere, significantly changing the plasma environment. Curtis and Grebowsky[21] showed that the bulk of the injected ion beam is not stopped in the magnetosphere. However, the relatively small fraction of the beam that is not stopped may give rise to a large distortion in the magnetospheric plasma population. They also evaluated possible loss mechanisms from the magnetosphere for this artificial ion component.The interaction of the heavy ions and the surrounding magnetized plasma field has been studied by particle simulations using hybrid code, where motions of ions are solved as particles while electrons are treated as a neutralizing fluid. As an initial response to the injection, a shock structure can be formed in the ambient plasma along with generation of magneto-hydro-magnetic waves and associated heating of the background plasmas. It has to be noted that heating processes and parametric instabilities may also take place within the plasmasphere, in the neighborhood of the satellite. The plasma is less dense but there is a high level of wave activity. The artificial generation or loss of extremely low (ELF) and ultra low (ULF) frequency waves in that region may have consequences on the dynamics of the radiation belts.

MPT on Human health and bio-effects

The concept of solar-power satellites (SPS) and wireless-power transmission (WPT) envisions the generation of electric power by solar energy in space for use on Earth[22][23], The system would involve placing a constellation of solar power satellites in geostationary Earth orbits. Each satellite would provide between 1 and 6 GW of power to the ground, using a 2.45 or 5.8-GHz microwave beam (see Table 1). The power-receiving rectenna on the ground would be a structure measuring 1.0 to 3.4 km in diameter. The higher (5.8 GHz) frequency has been proposed since it has a similar atmospheric transparency. Although, in principle, the higher frequency could involve a reduced size for the transmitting and receiving antennas, it can be seen from the table that current designs have opted for larger transmitting antennas and smaller rectenna sites, but a larger power density on the ground to conserve land use, especially in Japan. A joint effort between the Department of Energy (DOE) and the National Aerospace Administration (NASA) in the US extensively investigated the feasibility of SPS-WPT during 1976-1980. The effort generated a Reference System Concept for Solar Power Satellites. The DOE–NASA Reference System involved placing a constellation of solar power satellites (5 x 10 x 0.5 km deep) in geostationary Earth orbits, each of which would provide 5-GW of power to major cities on the ground, using a 2.45-GHz microwave beam. The Reference System's sixty satellites were contemplated to deliver a total of 300 GW of generating capacity.

Table 1 Typical parameters of SPS transmitting antenna

Model	Old JAXA model	JAXA1 model	JAXA2 model	NASA-DOE model
Frequency	5.8 GHz	5.8 GHz	5.8 GHz	2.45 GHz
Diameter of transmitting antenna	2.6 kmϕ	1 kmϕ	1.93 kmϕ	1 kmϕ
Amplitude taper	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian	10 dB Gaussian
Output power	1.3 GW	1.3 GW	1.3 GW	6.72 GW
Maximum power density at center	63 mW/cm^2	420 mW/cm^2	114 mW/cm^2	2.2 W/cm^2
Minimum power density at edge	6.3 mW/cm^2	42 mW/cm^2	11.4 mW/cm^2	0.22 W/cm^2
Antenna spacing	0.75 λ	0.75 λ	0.75 λ	0.75 λ
Maximum power per one antenna (Number of elements)	0.95 W (3.54 billion)	6.1W (540 million)	1.7 W (1,950 million)	185 W (97 million)
Rectenna Diameter	2.0 kmϕ	3.4 kmϕ	2.45 kmϕ	10 kmϕ
Maximum Power Density	180 mW/cm^2	26 mW/cm^2	100 mW/cm2	23 mW/cm^2
Collection Efficiency	96.5 %	86 %	87 %	89 %

The transmitting antenna was about 1 km in diameter. The power-receiving rectenna on the ground was a 10 x 13-km structure.Japan's Ministry of Economy, Trade and Industry (METI) had announced plans to launch research for a solar-power-generation satellite and to begin operating a giant solar-power station by 2040. This program is expected to design and operate an SPS-WPT system that would ensure the microwaves would not interrupt cellular mobile telephone and other wireless telecommunications services.The Japan Aerospace Exploration Agency (JAXA) has proposed and evaluated various system configurations for operation at 5.8 GHz (see Table). For example, the JAXA2 model would have a maximum power density of 100 mW/cm2 (1000 W/m2) on the ground.A smaller transmitting system would have a density of 26 mW/cm2 (260 W/m2) at the rectenna site on the ground.A variety of environmental considerations and safety-related factors continue to receive consideration, albeit at a low priority level.The biological effects and health implications of microwave radiation have been a subject of study for many years[24][25][26]. In fact, the cumulative data have allowed the establishment of recommendations for safety levels for humans under a variety of exposure conditions. For example, the ICNIRP (and Japanese) guideline is 5 or 1 mW/cm2 for occupationally exposed vs. the general public, at either 2.45 or 5.8 GHz[27]. Although the corresponding limits for IEEE standards for maximum permissible human exposure to microwave radiation, at 2.45 or 5.8 GHz, are 8.16 or 10 mW/cm^2 averaged over six min, and 1.63 or 3.87 mW/cm2 averaged over 30 min, respectively, for controlled and uncontrolled environments,[28] the IEEE standards have recently been changed to the similar one to that of the ICNIRP. [29] The controlled and uncontrolled situations are distinguished by whether the exposure takes place with or without knowledge of the exposed individual, and is normally interpreted to mean individuals who are occupationally exposed to the microwave radiation, as contrasted with the general public.As can be seen from the Table, the proposed power densities range from 23 to 180 mW/cm2 above the rectenna at the center of the microwave beam, where power densities would be maximum. At 2.45 GHz, the power density is projected to be 1 mW/cm2 at the perimeter of the rectenna. Beyond the perimeter of the rectenna or 15 km, the side lobe peaks would be less than 0.01 mW/cm2. Clearly, beyond the perimeter of the rectenna, the potential exposure would be well below that currently permissible for the general public.The danger of loss of control of highly focused beams may be minimized by tightly tuned phased-array techniques and by automatic beam defocusing to disperse the power if loss of control occurs. Defocusing would degrade the beam toward a more isotropic radiation pattern, which would give rise to even lower power density on the ground[30]. Near the center of the microwave beam, power densities would be greater than the permissible level of exposure for controlled situations. Except for maintenance personnel, human exposure would normally not be allowed at this location. In the case of occupationally required presence, protective measures, such as glasses, gloves and garments could be used to reduce the exposure to a permissible level.However, at 25 mW/cm2, research has shown that some birds exhibit evidence of detecting the microwave radiation. This suggests that migratory birds, flying above the rectenna, might suffer disruption of their flying paths. Moreover, at higher ambient temperatures, larger birds tend to experience more heat stress than smaller ones, during 30 min of exposure. This result is consistent with the knowledge that the larger birds, having a larger body mass, absorb a relatively greater quantity of microwave radiation than do the smaller birds[31]. The additional heat, from microwave energy deposited inside the body, could be stressing the thermal regulatory capacity of the larger birds. Thus to assure environmental health and safety, the proposed limit for the "center-of-beam" power densities is approximately 25 mW/cm^2 for microwave transmission.Note that the average absorption remains fairly stable for frequencies above 2 GHz,[24][32]except when the frequency becomes much higher,i.e., 10 GHz, where the skin effect takes over, the maximumtolerable exposure at 5.8 GHz would be essentially the same as for 2.45 GHz.We have to discuss the microwave (over GHz) effect on human health imposed by the SPS system. There is a long historyconcerning the safety of microwave energy. Contemporary RF/microwave standards are based on the results of critical evaluations and interpretations of the relevant scientific literature[34]. The specific absorption rate (SAR) threshold for the most sensitive effect considered potentially harmful to humans, regardless of the nature of the interaction mechanism, is used as the basis of the standard. The SAR is only related to a heating problem, which is regarded as the only microwave effect on human health.Discussions about the maximum microwave power density inside the rectenna site are necessary. The maximum power density depends on the antenna size and the frequency, which directly affect the total cost. In the present JAXA2 model, the microwave power density is 100 mW/cm2 at the center of the rectenna site, which is above the safe level. This area should be strictly controlled. Outside of the rectenna area, the intensities are kept below the safe level. A possible change of the safe level in the future could cause changes of the SPS design.

ADVANTAGES OF SPACE SOLAR POWER

1. Unlike oil, gas, ethanol, and coal plants, space solar power does not emit greenhouse gases.
2. Unlike bio-ethanol or bio-diesel, space solar power does not compete for increasingly valuable farm land or depend on natural-gas-derived fertilizer. Food can continue to be a major export instead of a fuel provider.
3. Unlike nuclear power plants, space solar power will not produce hazardous waste, which needs to be stored and guarded for hundreds of years.
4. Unlike terrestrial solar and wind power plants, space solar power is available 24 hours a day, 7 days a week, in huge quantities. It works regardless of cloud cover, daylight, or wind speed.
5. Unlike nuclear power plants, space solar power does not provide easy targets for terrorists.
6. Unlike coal and nuclear fuels, space solar power does not require environmentally problematic mining operations.
7. Space solar power will provide true energy independence for the nations that develop it, eliminating a major source of national competition for limited Earth-based energy resources.

CONCLUSION

A solar power satellite system, capable of transferring the required amount of power without using wire and all the atmospheric & environmental effects has been studied successfully. The maximum transferrable power is thus only a matter of the tolerable level of resistive losses. The vast applications for wireless power transmission delivers no small amount of motivation to this pursuit and certainly promises a beginning of an exciting new future in the energy industry and will have massive impacts throughout our everyday lives. However the technology is still young and it will be interesting to monitor its development through the course of the next few years. It's easy to see where wireless power transfer will better our lives, eliminating excess cables and wires, removing unnecessary clutter and the need for cleaning, allowing us even greater mobility with our devices and also allowing us to inhabit, in today's standards, uninhabitable areas. Furthermore it allows us to build cleaner, and certainly cheaper and environmentally friendly solutions of sustainable energy and it will bring us one step close in solving the world's energy crisis. It is More Reliable than ground based Solar Power Generation and wired electricity transmission. In order to have wireless electricity transmission to become a reality, following things have to happen.

- Government support
- Cheaper Launch Prices
- Involvement of Private Sector

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